

Astrotech 21 Workshop Proceedings:
Optical Systems Technology for Space Astrophysics in the 21st Century

SECTION IV (Cont'd)
WORKSHOP PANEL REPORT:

4. OPTICAL TESTING

James Wyant, WYKO Corporation, Chair

Eric Hochberg, Jet Propulsion Laboratory, California Institute of Technology, Co-Chair

Optical Testing Panel Participants

Robert Breault	BRO Incorporated, Tucson
John Greivenkamp	University of Arizona, Optical Science Center
Gary Hunt	Marshall Space Flight Center
Pete Mason	Jet Propulsion Laboratory, California Institute of Technology
James McGuire	Jet Propulsion Laboratory, California Institute of Technology
Aden Meinel	Jet Propulsion Laboratory, California Institute of Technology
Mike Morris	University of Rochester
Larry Scherr	Aerojet Corporation
Eldred Tubbs	Jet Propulsion Laboratory, California Institute of Technology
Tom Wolfe	Eastman Kodak Company

INTRODUCTION

Optical testing is one of the most vital elements in the process of preparing an optical instrument for launch. Without well understood, well controlled, and well documented test procedures, current and future mission goals will be jeopardized. We should keep in mind that the *reason* we test is to provide an opportunity to catch errors, oversights, and problems *on the ground*, where solutions are possible and difficulties can be rectified. Consequently, it is necessary to create *tractable* test procedures that truly provide a measure of the performance of *all* optical elements and systems under conditions which are close to those expected in space. Where testing is not feasible, accurate experiments are required in order to perfect models that can exactly predict the optical performance. As we stretch the boundaries of technology to perform more complex space and planetary investigations, we must expand the technology required to test the optical components and systems which we send into space. As we expand the observational wavelength ranges, so must we expand our range of optical sources and detectors. As we increase resolution and sensitivity, our understanding of optical surfaces to accommodate more stringent figure and scatter requirements must expand. Only with research and development in these areas can we hope to achieve success in the ever increasing demands made on optical testing by the highly sophisticated missions anticipated over the next two decades.

Testing is not a static art. Developments over the last decade, such as digitized figure measurements, have improved test capabilities enormously. However, continued development in this area is essential. The technological progress required for testing optical components and systems for future observational instruments depends heavily on the wavelength at which the experiment will be conducted, the scale of the instrument, and the overall scientific objective of the mission. In some cases, improvements are imperative across the entire frequency range. For example, improvements are required in the resolution, speed, and accuracy of

measuring large-aperture aspheric mirror surface figures in a gravity-free, space-like environment. This is necessary for virtually all of the Astrotech 21 missions.

Some specific wavelength ranges, however, will require a considerable amount of additional effort. For example, in the x-ray region many technological barriers exist. We need to better understand how to test the shape and tolerances of grazing-incidence x-ray optics; improve x-ray sources, detectors, and collimators; extend measurements of surface roughness to near atomic dimensions; and determine the effect of subsurface damage on the off-axis mirror scatter. In addition, at these wavelengths, advances in polarization-based metrology, spectropolarimeters, and imaging polarimeters are necessary to reduce polarization aberrations. X-ray material properties, such as refractive index and reflectivity, are not currently available, thus compounding the problem of testing. Fundamental measurements such as these will have to be made before optical testing can be accomplished.

Different technological needs drive the innovations necessary in optical testing in other wavelength regions. For example, in the far infrared region where telescopes, such as SIRTf, are expected to operate for many years at LHe temperatures, much work is required to understand the effect of temperature on the optical components and the overall system performance. How does the mirror figure or off-axis scatter change with temperature, and how do we measure these accurately at <10 K? How do we calibrate these changes and how do we measure and predict the effect of contamination on these super-polished mirror surfaces? The technology is available to answer some of these questions, but cryogenic material data, high vacuum, cryogenic test equipment facilities and a better understanding of both operating and testing optical systems at these temperatures are critical to the success of infrared missions. Such a facility for technology development in the x-ray, but not the infrared, region has already been built at the NASA Marshall Space Flight Center for testing optics

on the AXAF program. NASA should not delay in providing equipment and facilities, which are needed *now*, for testing in the infrared spectral region. It takes a long time to set up cryogenic equipment which can be counted on to test optics successfully at these temperatures.

These and other topics were the primary concerns expressed by the Optical Testing panel. Results and recommendations arising from discussions that occurred during the workshop are presented below and in Table 29. Where appropriate, the pertinent recommendations of other groups are also included (e.g., Fabrication, Wavefront Sensing).

Optical parameters were condensed into six areas:

1. Surface Figure
2. Surface Roughness
3. Alignment
4. Image Quality
5. Radiometric Quantities
6. Stray Light

In many cases the panel felt that the optical testing requirements of the mission set could be approximately met with existing technology or extensions of existing methods. However, many of

these missions are likely to push existing capabilities to the point where practicality and reliability of the results will be questionable. The modifications and extensions of existing technologies will greatly increase the difficulty of testing, increase the testing time, and introduce additional uncertainties into the test data. We need to simplify, speedup and improve the accuracy of existing test methods as the scale and complexity of space optical systems increases.

The performance of complete optical systems must be ensured with optical validation testing of components, subassemblies and, when practical, complete assemblies. This includes measurement of both component performance (surface figure of the individual segments in a segmented primary for example) as well as the quality of the "assembled" wavefront arriving at the science detector. The panel also felt that full-up system optical performance can be ensured by means of testing of active/adaptive optical systems whose demonstration will serve to ensure that all "on-orbit" disturbances to the optical train can be accounted for and corrected. In this regard, optical testing work closely dovetails with the work being done in wavefront sensing, control and pointing, and optical fabrication.

Table 29. Recommended Optical Testing Technologies for Astrophysics Missions : 1992-2010

TECHNOLOGY AREA	OBJECTIVES	REQUIRED DEVELOPMENT	MISSIONS IMPACTED	TECH. FREEZE DATE
Surface Figure	Measure the Surface Figure Parameters Including rms, p-v, Absolute ROC of Large-Aperture Aspheric Surfaces With High Spatial Resolution and Speed	Aspheric Measurements Test of Large Convex Secondaries Gravity Compensation Testing Cryogenic Measurements Sources and Detectors X-Ray Mirror Testing	AIM NGST (FFT) II LDR SMMI SIRTF AXAF XST, SMIM HXIF	'97 '02 '04 '01 '05 '92 '90 '95, '96 '99
Surface Roughness	Measure Surface Roughness Parameters Including rms, p-v and Power Spectrum	Stitching Software Sub-Surface Damage Measurement Sampling Statistics on Large Curved Surfaces	NGST AIM II	'02 '97 '04
Alignment	Assembly and Alignment of Optical Systems, Ground-Based, Lunar Surface and Deployable	System Assembly Techniques Figure Initialization Star Simulators Alignment Software Laser Gauges	AIM NGST (FFT) II LDR SMMI AXAF XST, SMIM	'97 '02 '04 '01 '05 '90 95, '96
Image Quality	Measure the Overall System Performance by Monitoring the Image Quality (e.g., Encircled Energy)	Modeling Sources and Detectors System Wavefront Measurements	AIM NGST (FFT) II LDR SMMI SIRTF AXAF XST, SMIM HXIF	'97 '02 '04 '01 '05 '92 '90 '95, '96 '99
Radiometric Quantities	Measure Radiometric Quantities, such as Transmission Reflectivity, Absorption, Radiance, Irradiance, Vignetting, and Polarization	Reflectivity Measurements Metrology Data Base Calibration	AIM NGST (FFT) II SMILS SIRTF XST, SMIM HXIF	'97 '02 '04 '01 '92 '95, '96 '99
Stray Light	Stray Light Measurements, Predictions, and Monitoring to Satisfy Mission Requirements	Stray Light Control BRDF Stray Light Testing Signatures Sources and Detectors Scatter Measurements Calibration	All	'95

SURFACE FIGURE

A. Technology Assessment

Surface figure measurement is fundamental to the characterization of the individual reflective optical components that make up a system. The Astrotech 21 mission set requires ground-based measurements of large aperture surfaces (e.g., Figure 30) to determine parameters such as the absolute radius of curvature and the rms and peak-to-valley surface figure errors. This data is required at high spatial resolution and at high speed. A large fraction of the measured surfaces will be aspheric. A requirement also exists for improved accuracy (into the 1 nm range).

The most common method of testing optical surfaces and wavefronts is interferometry. Interferometric surface figure testing is done by

constructing interferometers that include the surface to be tested. Figure 31 illustrates an infrared, phase-measuring interferometer of the Twyman-Green type, one of the most common interferometric configurations. Infrared interferometry can be useful for figure evaluation during the early stages of fabrication before polishing, and for rough testing of aspheric surfaces. Interferograms are recorded and analyzed to determine the surface shape.

When surface errors are large compared to the reference surface (in terms of the interferometric metrology wavelength) the resulting fringe patterns can become exceedingly complex and difficult to accurately convert into surface topography (Figure 32). Additionally, multiple interferograms are typically required so as to unambiguously discriminate between "hills and valleys."

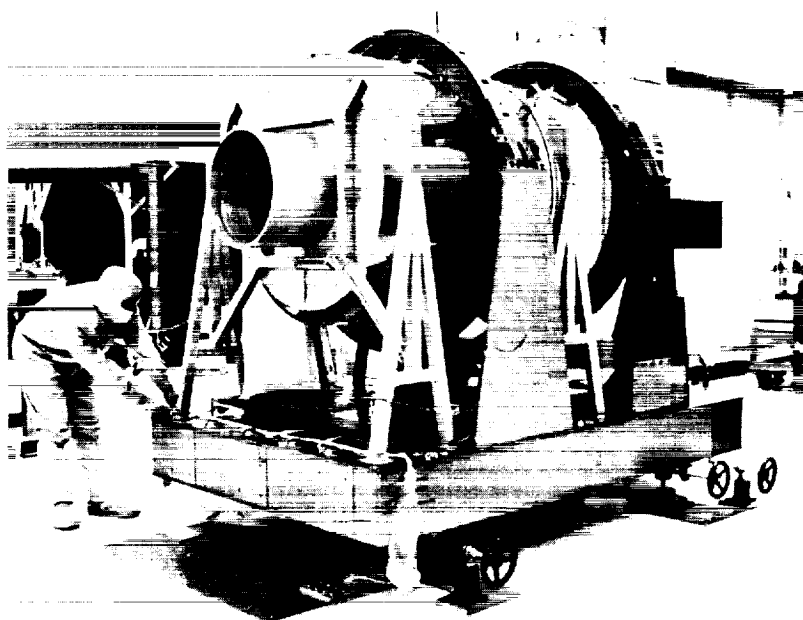


Figure 30. AXAF Optics Test – In June 1991, Kodak technicians and engineers successfully mounted the largest (48 in. diameter) of two special grazing incidence optics for AXAF. The optics are intended initially for use in a ground-based demonstration of the ability of the optics to precisely focus x-ray energy. This x-ray test was successfully conducted in September 1991 at a unique NASA x-ray test facility located at MSFC. A significant challenge addressed and overcome by Kodak was the development and implementation of a strain-free mirror mount, rugged enough to safely support the 500-lb fragile optic throughout the ground handling and transportation environment. To accomplish this, the mirror was bonded to 12 Invar tangential flexures that stabilize the mirror in all degrees of freedom while providing the radial compliance needed to minimize thermal and structural loads. (Courtesy of Eastman Kodak Company.)

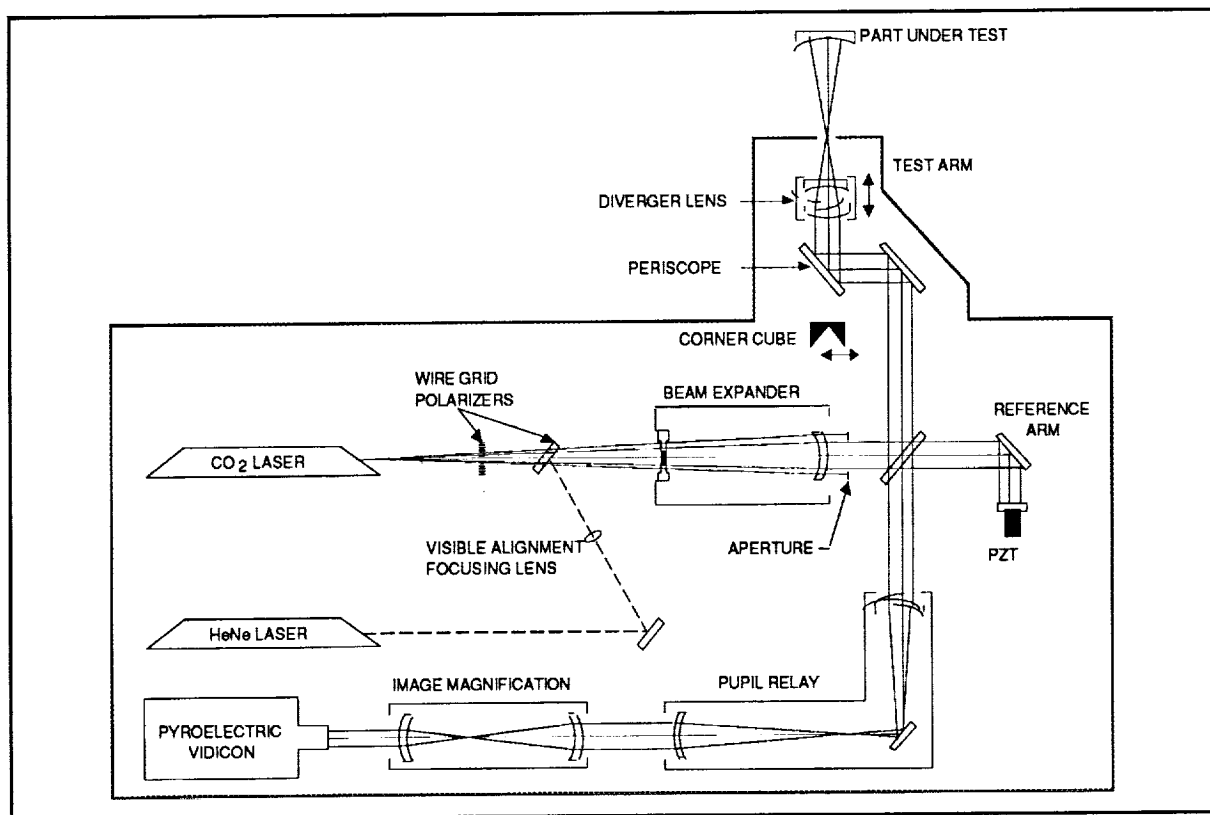


Figure 31. Twyman-Green Infrared Phase-Measuring Interferometer
(Courtesy of Breault Research Organization, Inc.)



Figure 32. Null Interferogram – Showing 10.6 μm 'null' interferogram of a large composite mirror. Note complexity of fringes. (Courtesy of Jet Propulsion Laboratory/California Institute of Technology.)

These multiple interferograms are usually acquired serially rather than in parallel resulting in increasingly extreme demands on the stability of the test setup — particularly as the dimensional scale of the test setup increases. High speed measurement will also become increasingly important when it comes to meeting cryogenic test requirements in which even this relatively short metrology "snapshot" can result in significant heat loading on the test article.

Vibration may or may not be a problem depending upon a number of factors including: (1) the test methodology (mechanical, ray or wave-based); (2) the dimensional scale of the optics under test; (3) frequency and amplitude of the vibration; (4) the wavelength of test and/or the desired resolution and accuracy; (5) the intrinsic quality of the surface or wavefront; and (6) sampling rate requirements. If vibration causes the surface or wavefront to be unstable over the course of the measurement, the measurement may be compromised. For example, when certain interferometric techniques are employed, the measurement acquisition time must be made short for the fringe contrast degradation to be made acceptably small. When phase-shifting techniques are used (as are typically required when the surface errors cannot be unambiguously resolved in a single interferogram), then wavefronts must be kept stable over the entire phase-shifting cycle. [Note high speed or instantaneous phase shifting interferometric techniques have been recently developed (see Refs. 1, 2, and 3) in response to requirements for vibration immunity and/or high measurement bandwidth.] Common-path and shearing interferometric techniques as well as a number of ray-based optical tests founded on geometrical optics principles [e.g., slope or curvature sensing (see Refs. 4 and 5) or PSF inversion] may be intrinsically more robust with respect to vibration insofar as they allow the effects of vibration to be "averaged out" with sufficient integration time. Essentially, a variety of wave- and ray-based vibration-tolerant metrologies have successfully made possible the testing of large optical elements and systems in conventional, non-vibration-isolated environments. At this point in time, it appears fairly

clear that vibration is not likely to be a major technology hurdle for future optical testing.

A limited capability to test aspheric surfaces currently is available. Most tests require a null optic (refractive, reflective or diffractive; see Offner null lens example in Figure 33) to compensate for the asphericity of the surface and to reduce the number of fringes in the interferogram. In addition to being hard to design and fabricate, the performance of the nulls is also difficult to validate, and errors in the nulls or their alignment translate into apparent errors in the surface under test. Some aspherics can be tested in null configurations against flats or spheres, but these tests are often impractical due to the size requirements placed on these auxiliary optics. The current approach to testing aspherics must be reconsidered as surfaces to be tested become larger and more aspheric.

Testing convex surfaces has always been a challenge simply from a practical perspective — typically, the required reference surface (Hindle sphere) must be substantially larger than the surface under test. Figure 34 schematically shows a Hindle test of a convex hyperboloid. For secondaries larger than 1 m, this approach is clearly impractical; a reference surface does not exist and would be impractical to fabricate. The current approach is to test subapertures of the surface and stitch or assemble these subaperture results together to obtain the full surface. While this approach is used, it is inconvenient and unreliable. New technology to allow for the testing of large convex surfaces is needed. This technology will impact the missions with primaries larger than 4 m (AIM, NGST, FFT, LDR, and LSMM).

The shape and tolerances of grazing-incidence x-ray optics present unique problems in their testing. The limited technology that exists for this application relies primarily on measuring one-dimensional longitudinal surface profiles of the mirrors. New technology is clearly needed for the x-ray missions. Representative of the state of the art in x-ray test facilities is the x-ray calibration facility at

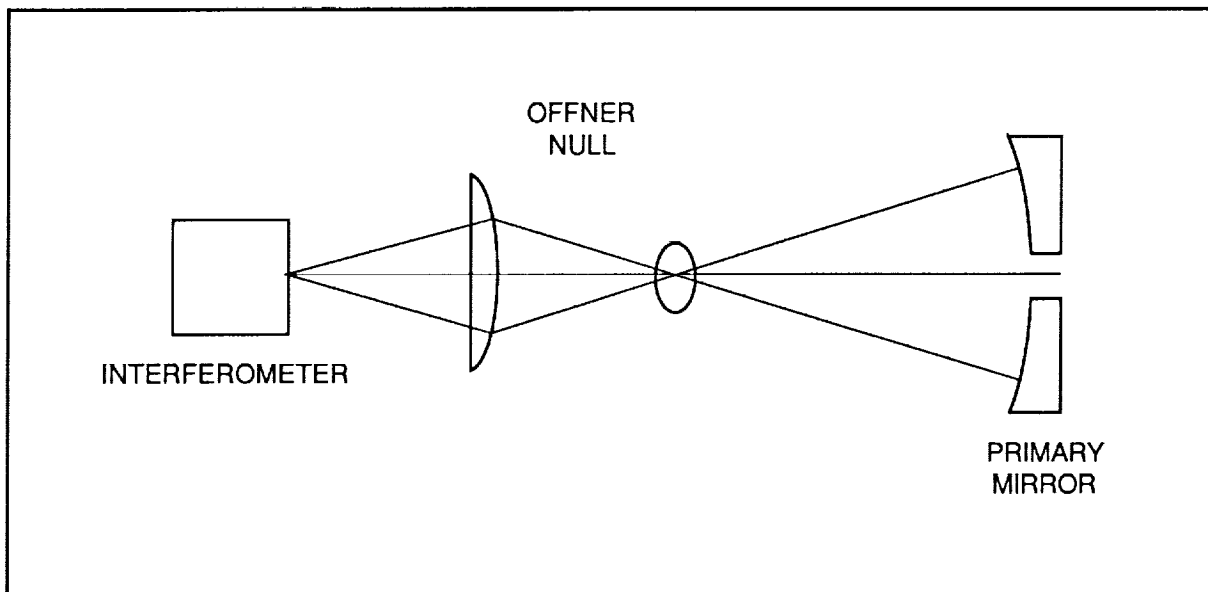


Figure 33. Offner Null Lens

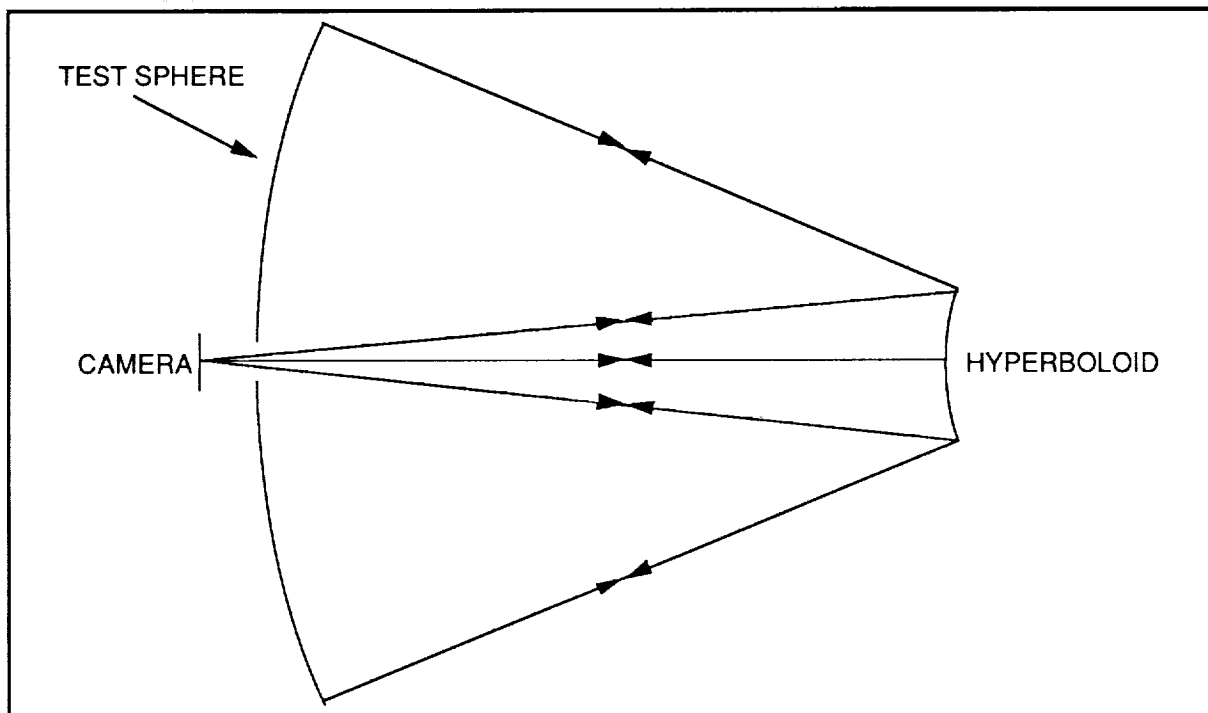


Figure 34. Hindle Test for Convex Hyperboloid

MSFC (This is the test facility that was used to verify the AXAF P1/H1 mirror performance).

The MSFC X-ray Calibration Facility (XRCF) provides a 57.5 in. dia, near-parallel beam of x-rays for ground test and calibration of x-ray telescope optics and experiments. The XRCF comprises vacuum systems, clean rooms, x-ray generator and monitor systems, data acquisition and control systems, test hardware handling systems, and associated support hardware. The XRCF vacuum envelope consists of a 24-ft-wide by 60-ft-long Instrument Chamber (IC) connected to the east side end of a 3- to 5-ft-diameter by 1700-ft-long Guide Tube. The west end of the Guide Tube is joined to Alignment and Source Chambers, which provide interfaces for the XRCF Alignment Telescope, Alignment Laser, and x-ray generator assembly. To maintain the cleanliness levels required for optical testing, all vacuum systems are rough-pumped with dry mechanical or cryogenically trapped mechanical pumping systems. High vacuum pumping (to the 10^{-7} torr pressure range) is accomplished using cryogenic and turbomolecular pumping systems.

The X-ray Generator Assembly (XGA) is a multifocus type bremsstrahlung source of selectable energies filtered for spectral purity. The XGA provides x-ray energies over the range from 0.2 to 8.1 keV at flux levels from 0.1 to 1000 photons/(sec \cdot cm²) at the instrument chamber. Calibrated x-ray monitors measure the x-ray flux to within 10% accuracy. Optical baffles are located along the length of the guide tube to prevent scattered radiation from reaching the entrance aperture of the hardware under test. To track dimensional drift in the XRCF, a motion detection system is available. The motion detection system can be used to measure relative motion of the test optics, focal plane instruments, and the x-ray generator support structure to within 0.2 μ m. Access to the IC is gained through a 5900-ft² class-10,000 clean room. A 2300-ft² class-10,000 clean room is used as a receiving area for the IC clean room. Entry into the IC is provided via a 24-ft-diameter removable dome. Test hardware is staged into the IC clean room

and mounted on movable test benches using a 20-ton bridge crane. The test benches supporting the test hardware are rolled into the IC using a rail system with Thompson bearings and offloaded onto the rail system support piers. To isolate the optical hardware under test from externally induced vibration, the support piers are isolated from the IC wall using complaint vacuum bellows and are mounted to a 5-ft-thick seismic pad. A 48-in. entry port is located on the IC 24-ft removable dome to provide for personnel access and to transport small hardware into the IC. In a typical test, the x-ray optical test hardware is mounted in the west end of the IC on the facility optical axis. The x-ray detector hardware is located near the east end of the IC at the focus of the x-ray optics. The alignment laser and telescope are used to precisely align the test hardware to the facility optical axis. The facility is evacuated, the x-ray generator is activated, and a known x-ray environment is provided to test the X-ray performance of test hardware.

The MSFC XRCF is unique in that it provides an optically clean, dimensionally and thermally stable, high vacuum test chamber with a well collimated x-ray beam, clean rooms, and other previously mentioned capabilities into the largest facility of its type in the world. It was originally constructed in 1990–1991 to measure the x-ray optical performance of the Advanced X-ray Astrophysics Facility (AXAF) Verification Engineering Test Article No. 1 (VETA-1) optics. Modifications are currently in design to enhance the capabilities of the XRCF. These modifications include upgrading the IC clean room to better than a class 1000, adding additional high vacuum pumping to accommodate the increased gas loads imposed by large test hardware, and upgrading the IC thermal control system to provide for a spatially uniform and temporally stable thermal environment over the temperature range from -60°F to +160°F. Modifications are also planned that would extend the energy range and increase the spectral purity of the x-ray generator assembly. After modification, the XRCF will be used for ground testing of the AXAF High Resolution Mirror Assembly (HRMA) and Science Instruments (SIs).

For many systems, it is desirable or necessary to test the surface or component at the wavelength it will be used (for example, transmissive components). The important parameters for sources include uniformity, stability, and coherence while important detector parameters are number of pixels, response time, uniformity, and responsivity. For tests in the visible and the near-IR, there are ample sources and detectors. This same situation does not exist at other wavelengths especially from the mid-IR out to the submillimeter. Improved x-ray sources and collimators are also needed. While it is unlikely that testing alone can justify the development of new source and detector technology, NASA should encourage this development and modify and learn to use this technology as it becomes available.

It is critically important to measure, at least at the component level, the surface figure of optical elements that will be operating at cold temperatures. (This need was also highlighted by the optical

fabrication group.) Optics for the submillimeter telescope missions call for figure quality at temperatures between 100 K and 200 K and may include significant thermal spatial gradients over the aperture. The LHe-cooled SIRT primary must have a good surface figure when actively cooled to <10 K. Surface figure must be measured, inferred, or predicted with high confidence at these temperatures. Test limitations are primarily in large cryogenic test facilities which present design challenges in vibration control, isolation, insensitivity, and invasiveness for the test metrology. The present state of the art for 632.8 nm systems (Rome Air Development Center, New York) is video rate (15 ms figure measurements), 128^2 pixels spatial resolution integrated with a 2.0 m class LN_2 cryogenics chamber. A schematic of a phase-shifting interferometric workstation (generic) is shown in Figure 35. Improvements in spatial resolution are being realized primarily with higher pixel density detectors.

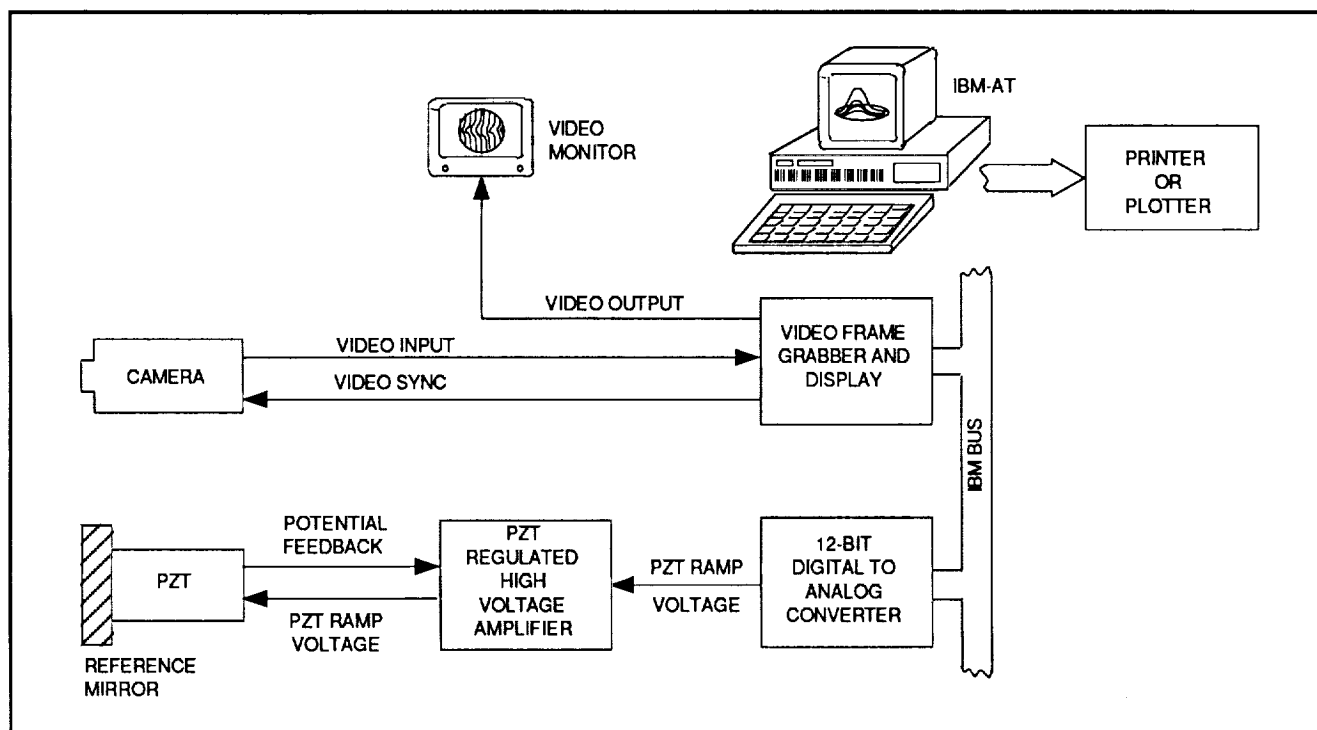


Figure 35. Phase-Shifting Interferometric Workstation. (Courtesy of Breault Research Organization, Inc.)

B. Development Plan

New interferometric technology must be developed that will allow for the detection and interpretation of more complicated fringe patterns to reduce the requirements placed on existing detectors and null optics. In addition, improved calibration procedures are needed to push the accuracy of these tests towards the 1 nm level from their current level of about 10–21 nm. These improvements in aspheric testing will undoubtedly require the interaction of ray tracing software with the interferometric software. Most of the missions in the mission set we are

considering will be able to make use of this technology.

The panel recommends that technology be developed in five specific areas: aspheric surface testing, testing of large convex secondaries, cryogenic measurements, sources and detectors for optical measurements, and the testing of grazing-incidence x-ray mirrors. (Need for development in these areas has also been highlighted by the optical fabrication panel.) Table 30 summarizes the Surface Figure technology area.

Table 30. Surface Figure Technology Development Program

TECHNOLOGY	CURRENT TECHNOLOGY	PROGRAM GOALS	NEED DATES	TECH. DEV. TIME FRAME
Aspheric Measurements	Hubble, Keck	1 nm Accuracy on f/1 surfaces	'97, '02, '04,	'92 -'04
Large Convex Secondaries	Keck	1 m Aperture	'97, '02, '04, '01, '05	'92 -'04
Cryogenic Measurements	SIRTF 0.5 m @ 10 K	Measurements at LN ₂ , LHe 1.0 m @ 2 K	'95, '02, '92	'92 -'03
Source and Detectors	VIS + Near IR	Mid IR to Submm and UV Resolution ; > 1000 ² Pixels X-ray Sources, : > 8.1 keV X-ray Flux Monitors : Better Than 10%	'90, '95, '99, '01	'92 -'02
X-Ray Mirrors	Limited	Improved Capability Test Facilities Large Beam Diameter : > 60"	'90, '95, '99, '03	'92 -'04

SURFACE ROUGHNESS

A. Technology Assessment

Technology developments in surface roughness measurements to measure parameters including root-mean-square (rms), peak to valley (p-v), and power spectrum at μm to centimeter spatial periods are needed for the majority of the missions for wavelengths shorter than the mid IR.

Optical profilers are commercially available for angstrom height measurements for spatial periods ranging from approximately one-half μm to several centimeters for flat and spherical surfaces. Cylindrical or general aspheric surfaces can be measured for spatial periods of a few mm. Small spatial period measurements can be stitched together to obtain larger period information. Additional software and hardware developments are required to properly align the subapertures without artificially introducing surface errors.

Only a limited area of large surfaces can be measured for surface roughness. The roughness statistics of flat surfaces do not vary much over the surface area, so only a few spots on the surface need to be measured. The BRDF on the other hand might vary more significantly and should be measured in more locations. This is not true for aspheric surfaces

where the surface statistics can vary considerably over the surface. Additional analytical work is required to determine the sampling requirements for large optical surfaces. Stitching software needs further development for mid spatial frequencies and to bridge the gap between low spatial frequency figure errors and high spatial frequency surface roughness.

B. Development Plan

Optical profilers for cylindrical and general aspheric surfaces need to be developed. The technology associated with accurately moving profilers over large surfaces, while maintaining absolute position knowledge of the measurement, is essential in developing full surface roughness models. Software that will take sectional measurements, and develop a full surface roughness profile and analysis needs to be developed.

The spatial frequency of roughness measurements needs to be extended to near atomic dimensions to support technology development of new fabrication techniques for the ultraviolet and x-rays, and to the large spatial frequency data required to close the gap between high frequency figure errors and surface roughness.

Finally, technology requiring development in measurement tools that will allow the relation of

subsurface damage measurement to final achievable surface roughness. This technology area is undeveloped.

Table 31 summarizes the recommended development program for three surface roughness technologies.

Table 31. Surface Roughness Enabling Technologies Program

TECHNOLOGY	CURRENT TECHNOLOGY	PROGRAM GOALS	NEED DATES	TECH. DEV. TIME FRAME
Stitching Software	Non-Existent	Software Development Integrating Figure and Roughness Testing	'95, '97, '02, '04	'93 - '04
Subsurface Damage	Limited, Mostly Destructive Techniques	Non Destructive Techniques Instrumentation Statistical Data	'95, '97, '02, '04	'93 - '04
Sampling Statistics	Cumbersome	Statistics on Large Surfaces	'95, '97, '02, '04	'93 - '04

ALIGNMENT

A. Technology Assessment

Alignment technology is perhaps the most primitive of all of the optical testing technologies. The basic alignment methods used for most large optical systems rely on surveying technology developed in the last century, augmented with HeNe pencil alignment beams and microprocessor readouts. The procedures used to align complex, multimillion-dollar optical systems are essentially ad hoc, with little or no model verification of the procedure before or during alignment.

The panel considered four technologies necessary to improve alignment and optical system assembly capability to meet the requirements imposed by the Astrotech 21 mission set. These technologies are:

1. Partially Assembled System Alignment
2. Segmented Optics Initialization
3. Laser Gauges
4. Marriage of Optical and Mechanical Software

B. Development Plan

Table 32 summarizes the recommended development program in alignment technology. The following paragraphs address the individual elements of the program.

Partially Assembled System Alignment is required in process in the assembly and test of optical systems containing large numbers of components. The technology is undeveloped, except for a few special case techniques. The development plans call for the modeling and design of partially assembled systems, with the test fixtures and mounts built into the overall system concept (Figure 36). Hardware and software developments will be required to capture and analyze the complex fringe patterns resulting from tests of partially assembled systems.

Segmented Optics Initialization is required for phasing large segmented optical systems. Some current development efforts are under way for submillimeter telescopes, but these are slow and cumbersome. Additional work in segment control is being pioneered by the Keck Observatory. Additional efforts are needed for high speed systems that converge rapidly in the presence of thermally induced distortions of mirrors and structures. The technology effort will be to simulate the various algorithms, the operating software and the mirrors, including distortions, diffraction, and high and low frequency spatial errors to demonstrate the ability to initialize a system.

Laser Gauges are used to measure dimensional changes of panels and structures. The current positional resolution is about 1.0 nm. The technology development plans call for improving this resolution by a factor of 10 to 0.1 nm. This resolution

is required for submillimeter antennas and for space interferometers.

Optical and Mechanical Software interactions are fairly limited. Some of the more sophisticated codes can read interferograms and NASTRAN-generated surface perturbations and use them to deform the optical surfaces. (Since the

spatial resolution of structural analysis codes is not high, this is rarely a completely thorough calculation.) The technology development plan requires the interactions to be fast, and accessible to users trained in both disciplines. This activity is addressed in more detail in the next panel report, 5. Optical Systems Integrated Modeling.

Table 32. Alignment Enabling Technologies Program

TECHNOLOGY	CURRENT TECHNOLOGY	PROGRAM GOALS	NEED DATES	TECH. DEV. TIME FRAME
System Assembly	Initial Evaluation	Alignment Techniques for Partially Assembled Systems	'97, '02, '04, '01, '05	'93 - '04
Figure Initialization	Cooperative Point Sources	Initialization and Phasing of Segmented Optics, in ALL Degrees of Freedom	'01, '02, '04, '05	'93 - '04
Star Simulators	DoD	Star Simulators for System Testing	'97, '01, '02, '04, '05	'93 - '04
Software	Few Disciples, Limited Data	Marriage of Optical and Mechanical Software Including Gravity, Mounts, and Thermal	'01, '02, '04, '05	'93 - '04
Laser Gauges	Good, Improvement Needed	Accuracy : ≤ 1 nm	'01, '02, '04, '05	'93 - '04



Figure 36. Verification Engineering Test Article (VETA) In Final Assembly – Technicians complete final wiring of the VETA prior to shipment to MSFC in early August 1992. The VETA (shown here without its thermal enclosure) used the largest pair of AXAF grazing incidence optics to successfully demonstrate the ability of the optics to form precise x-ray images. A significant challenge addressed and overcome was the development of a precise mirror alignment control subsystem. Alignment was achieved by supporting the secondary mirror on an ensemble of six submicron resolution actuators (not shown in this shipping configuration) arranged to provide 6 degree-of-freedom alignment control to 0.1 arcsec accuracy. (Courtesy of Eastman Kodak Company.)

IMAGE QUALITY

A. Technology Assessment

All systems, except for light buckets, need measurements of overall image quality. Image quality metrics include: encircled energy, Strehl ratio, the optical transfer function, and quality of the transmitted wavefront. The required measurements depends upon mission science requirements. For some missions it is only necessary to measure the image quality at a single field point, while for other missions many measurements over the field of view and for different wavelengths are required. More attention will need to be paid to polarization properties of system elements as well.

B. Development Plan

An important component of any overall system performance measurement is the light source used for the measurement. In many instances a high quality collimated source is required. Collimated sources with the requisite wavefront flatness and radiometric uniformity must be available for many different wavelengths. (Developments are especially

needed in the UV.) Also, both point and area array detectors are required for the measurements. There is little problem with detectors for the visible and near infrared, but technology development is needed for other wavelengths.

The optical systems required for some missions are so large it will probably not be feasible to measure the wavefront across the entire aperture and therefore subaperture measurements will be required. In these cases improved stitching software is required to go from the sub-aperture wavefront to the full-aperture system wavefront.

Required technology includes improved diffraction analysis and modeling. Vector diffraction analysis is required for missions using segmented optics, and Fresnel diffraction capability is required for some of the longer wavelength systems. By improving diffraction analysis capability, it will be possible to reduce the number of measurements required for different field angles and wavelengths. The effects of noise sources and misalignments can be reduced. Table 33 summarizes three Image Quality technology areas.

Table 33. Image Quality Enabling Technologies Program

TECHNOLOGY	CURRENT TECHNOLOGY	PROGRAM GOALS	NEED DATES	TECH. DEV. TIME FRAME
Modeling	Limited	Advanced Diffraction Analysis and Modeling Software	'97, '01, '02, '04,	'93 - '04
Sources and Detectors	VIS and Near IR	UV, Mid IR to Submm : Sources Point and Area Array Detectors	'90, '95, '99, '01, '02	'93 - '04
System Wavefront	Hubble, Keck	Full Aperture System Wavefront (Via Stitching)	'97, '01, '02, '04, '05	'93 - '04

RADIOMETRIC QUANTITIES

A. Technology Assessment

Polarization is important in systems that: measure total intensity (radiometers and spectrometers), measure polarization (polarimeters), are based upon interferometric principles

(interferometers, phased arrays), or use grazing incidence optics.

The goal of spectrometers and radiometers is to make accurate intensity measurements independent of incident polarization state. Because of the polarization properties of the optics, they are biased by the incident polarization. Currently

accuracies of 5% and 1% are realistic for grating based spectrometers and radiometers, respectively. To design more accurate spectrometers and radiometers, improved software analysis tools are required, chiefly a closer coupling between existing thin film, diffraction grating, and optical design software. Software for polarization analysis of binary optics is currently not available, but will be required if binary optics are used for any of systems discussed in this section. Analysis software for stress birefringence may be required for some instruments.

Polarimeters can be used to studying solar magnetic fields, solar flares, and quasars. Planned radiometers, interferometers and x-ray optics would benefit from advances in polarization based metrology, such as polarization BRDF which measure polarization dependent scatter, spectropolarimeters which measure wavelength dependent polarization, and imaging polarimeters. Polarization BRDF is a simple extension of standard BRDF measurements with a polarimeter instead of source and detector. Spectropolarimeters exist in the IR and visible but are calibrated to only 5%. Imaging polarimeters exist in IR and visible but lack accuracy. Polarimetric accuracy is limited by modulators in the IR, UV, and x-ray and lack of completely characterized (i.e., full Mueller matrix) polarization standards in all wavelengths bands.

Polarimetric accuracy is also limited by polarization changes by optics prior to the polarization modulators. Design of improved polarimeters requires new software models for birefringent and optically active materials in addition to the software requirements mentioned above.

In interferometers, interference can occur only between wavefronts with the same state of polarization. In this sense, polarization mismatch leads to a loss in fringe visibility and signal-to-noise. Design and fabrication of improved interferometers for both the science missions and metrology depend on

the improved polarization design software and polarization metrology tools discussed above.

The optics for grazing incidence, x-ray, and FUV instruments will have larger polarization aberrations resulting from operation at larger angles of incidence. The polarization aberrations from some single mirrors (e.g., AXAF) and mirror systems have been, or will be, large enough to produce observable polarization-dependent point spread functions and surface interferograms. This image degradation is in addition to degradation in radiometric and spectrometric performance. (Polarization aberrations may, of course, degrade image quality in any optical system, but will probably be negligible in all but the most sensitive such as the NGST). Design and analysis of improved x-ray optics depends on improved polarization design software and characterization of x-ray materials. Characterization of x-ray materials will require new techniques and devices to measure the complex refractive index.

B. Development Plan

There are two major technology developments that are required. The first is to develop the material data bases that allow proper designs to be built, tested and validated. Significant tests are required of the complex refractive index and reflectivity, particularly of ultraviolet and x-ray materials. This is a fairly low level continuing technology study area. There is no empirical polarization property data base available to system designers. The necessary test of materials must be made and documented in a usable catalog.

The second technology development is to increase the accuracy and capability of the measurement instruments. An order of magnitude improvement is needed in absolute radiometric calibration, polarization, and radiometric quantities.

Table 34 summarizes four technologies for Radiometric Quantities.

Table 34. Radiometric Quantities Enabling Technologies Program

TECHNOLOGY	CURRENT TECHNOLOGY	PROGRAM GOALS	NEED DATES	TECH. DEV. TIME FRAME
Reflectivity Measurements	Visible and Near IR only	Reflectivity Measurements (complex n) at UV and X-Ray Wavelengths	'97, '01, '02, '04,	'93 - '04
Metrology	10%	Polarization Metrology, Analysis of Components and Full Systems; 1%	'95, '97, '01, '02, '04,	'93 - '04
Database	Limited	Polarization Database	'95, '97, '02, '04,	'93 - '04
Calibration	10% absolute accuracy	Development of Absolute Radiometric Calibration Techniques; 0% absolute accuracy	'97, '01, '02, '04,	'93 - '04

STRAY LIGHT MEASUREMENT

A. Technology Assessment

Many of the Astrotech 21 missions will require very good stray light suppression. Several of the missions will have a bright source (star) near a dim object (planet). The dim object is often the critical object to be observed. In order to minimize stray light, there needs to be a good design; the design needs to have clean, low scatter optics, and the baffles need to be highly absorbing. An incorrect choice of any of these parameters can make a dramatic difference in system performance (Figure 37). Technology is required that will:

- (1) Correlate fabrication procedures with BRDF in order to identify processes that lead to lower scatter surfaces, low rms roughnesses, and particle-free surfaces. (Figure 38 illustrates the effect of polishing time on the BRDF of an optical surface.)

- (2) Cleaning of surfaces to restore the original low scatter characteristics.
- (3) Measured data to aid in the selection of materials for design and fabrication.
- (4) Simplified system-level stray light tests.
- (5) Polarization sensitive BRDF data.
- (6) Near angle scatter measurements.
- (7) Long life, stable, Lambertian reference calibration samples at UV and IR wavelengths.
- (8) Next-generation stray light analysis software with more extensive BRDF databases and polarization analysis capability.

To achieve some of the above data or measurements, there is an immediate need for higher-power sources and more sensitive detectors especially in the UV and far IR wavebands.

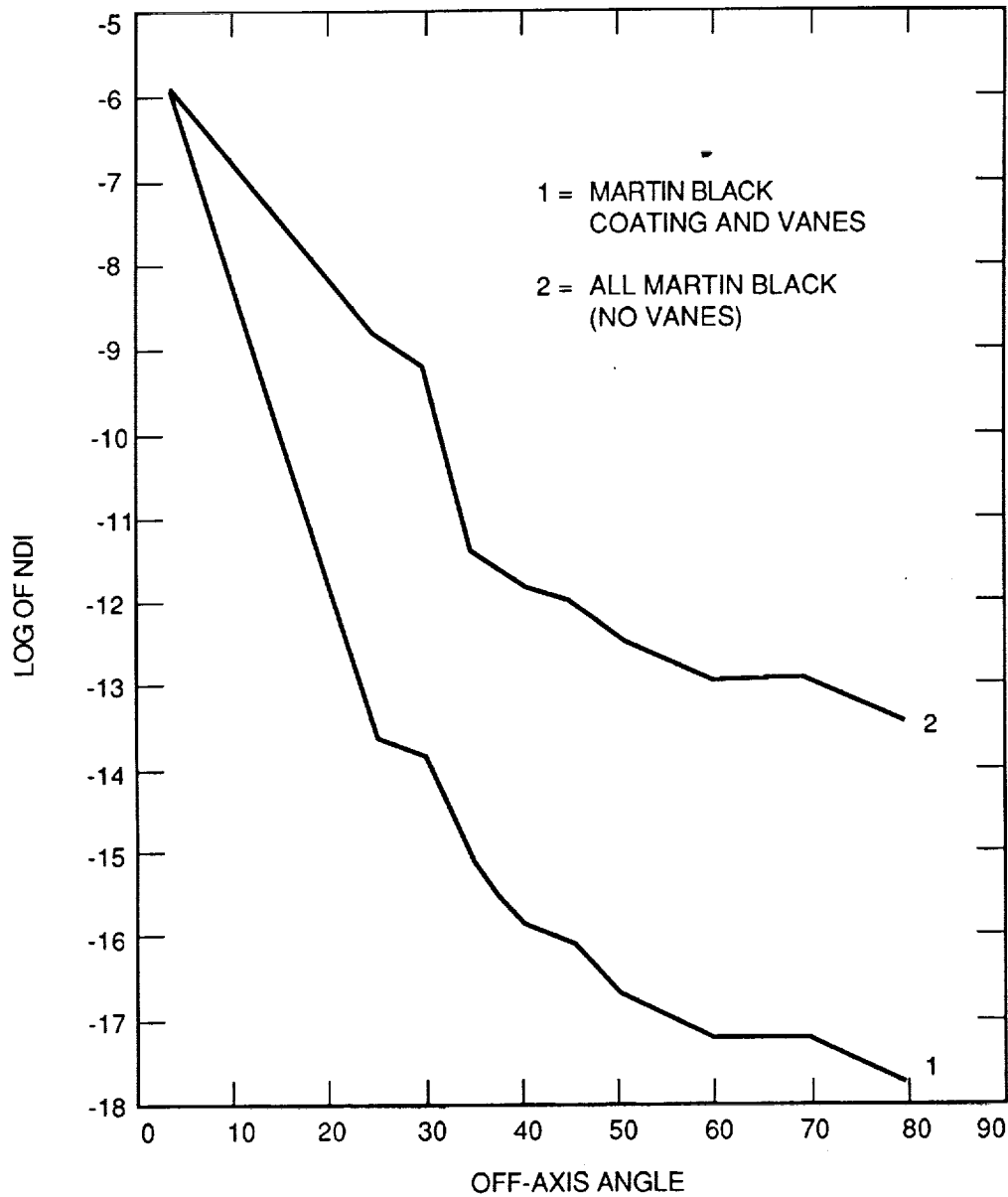


Figure 37. APART Analysis of SPACELAB 2 Telescope – The Normalized Detector Irradiance (NDI = detector irradiance/input irradiance) for a telescope with and without vane structure. (Breault Research report for the Smithsonian Institute, Cambridge, Massachusetts, "Analysis of the Small Helium-Cooled Infrared Telescope for Space Lab 2," 1977.)

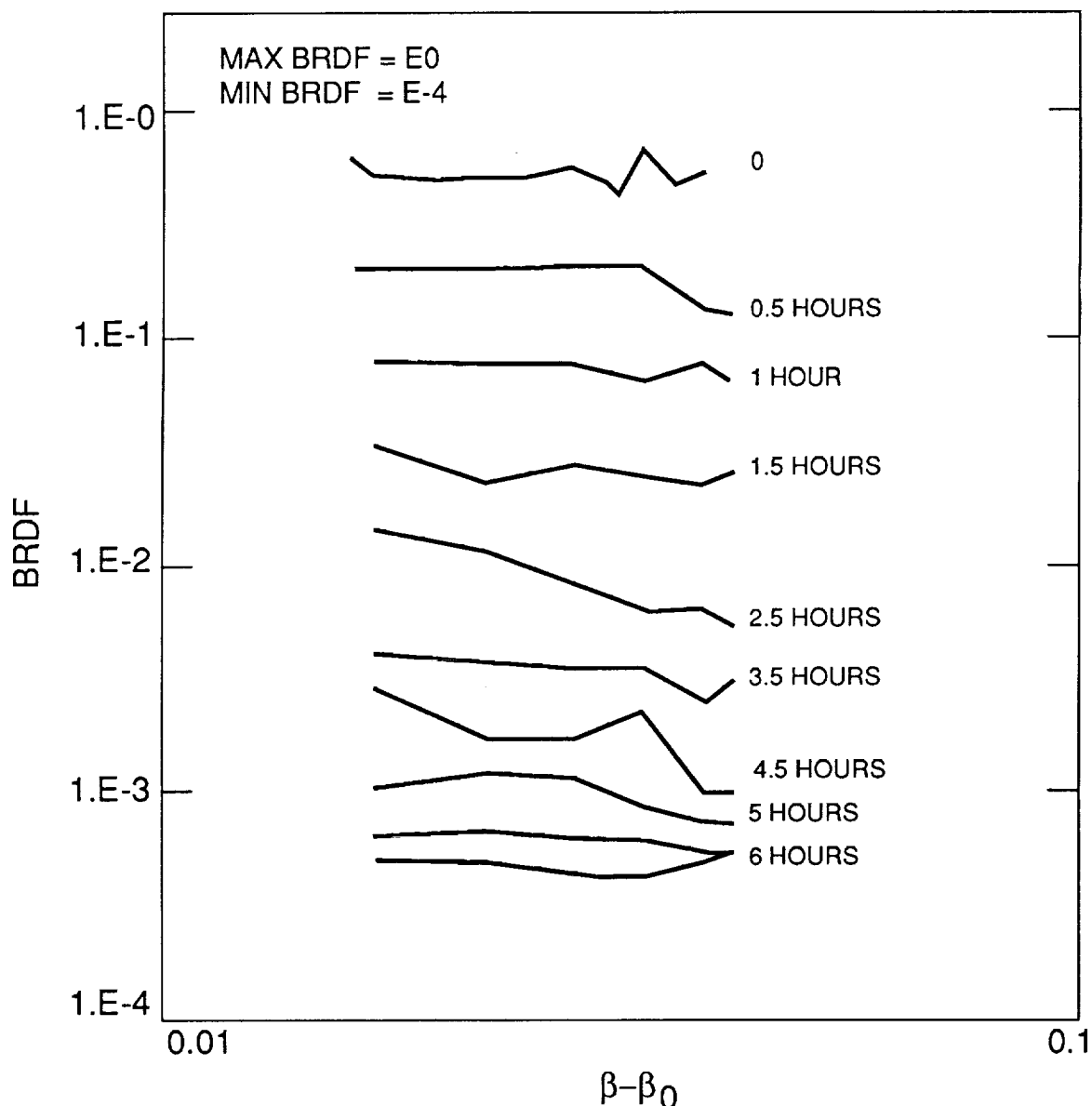


Figure 38. BRDF as a Function of Polishing Time in Hours. (Courtesy of Breault Research Organization, Inc.)

B. Development Plan

Taking the above issues one by one; lower scatter surfaces sometimes require lower surface roughnesses, but not always. A lower rms roughness will not help if the dominant scatter mechanism is due to particulate scatter or subsurface damage. For small (<15 cm in diameter) parts rms roughnesses <1 angstrom have been achieved. There is not much call for improvement here. There is room for

improvement on the very large surfaces that are being considered. Particulate scatter will probably dominate unless the mirrors are periodically cleaned. This is especially true for the near IR wavebands. The Air Force's Rome Air Development Center, under Captain Deidre Dykeman, is in the flight verification stage of cleaning space-based optics. Hopefully this will be accomplished by 1993. It holds the promise of decreasing the stray light background noise on systems like SIRTf by a factor of 100. Space-based

cleaning promises a great return on investment for long-life systems.

BRDF data below wavelengths of $0.4 \mu\text{m}$ and above $20 \mu\text{m}$ is almost nonexistent. BRDF data of black absorbing coatings in general shows a strong angle of incidence dependence (Figure 39 (a), (b), and (c)); additionally, black coatings in the $2 \mu\text{m}$ to $6 \mu\text{m}$ band show strong wavelength dependence. Wavelength sensitive BRDF measurements are needed in this wavelength region. NASA should fund the enhancement of existing facilities and the fabrication of vacuum UV BRDF instruments. Then data should be accumulated on mirrors, filters, lenses, and black coatings so that stray light analyses in the future will have realistic BRDF data to work with. This should not require a very expensive investment but it is needed now and is crucial.

Existing BRDF instruments (or scatterometers, an example of which is shown in Figure 40) can be modified to determine the polarization signature of mirrors, lenses, and coatings. The Mueller Matrices can be measured for the various materials. The results can be used in the scatter analysis and also in determining the radiometric characteristics of the sensors.

Currently most BRDF instruments use the "reference" method to calibrate their BRDF data. The mathematical justification for this approach is:

$$\Phi_{\text{DET_REF}} = \Phi_L \text{BRDF}_{\text{REF}} \Omega_{\text{DET}} \cos\theta$$

$$\Phi_{\text{DET_MIR}} = \Phi_L \text{BRDF}_{\text{MIR}} \Omega_{\text{DET}} \cos\theta$$

$$\text{BRDF}_{\text{MIR}} = \frac{\Phi_{\text{DET_MIR}}}{\Phi_{\text{DET_REF}}} \text{BRDF}_{\text{REF}}$$

Only in the visible spectrum is there a reliable and calibrated Lambertian reference material. NASA should fund the development and characterization of Lambertian reference materials for the UV, IR, and Far IR wavelength regions.

Each of the sensors should develop a plan to measure the system's stray light characteristics. Those systems that will only be assembled in space will need to be tested in parts, i.e., a full segment at a time if nothing else. The full range of off-axis angles will NOT need to be evaluated. A series of measurements near the FOV data will help significantly in verifying the expected performance in space. They verify that the most critical elements, the mirrors and other surfaces seen by the detector, are scattering in compliance with the analysis.

Very near angle scatter measurements are an important part of many of the missions. None of the existing BRDF instruments measure high quality, low scatter surfaces at angles less than about 0.5° . New methods are probably needed to evaluate the BRDF at angles much less than 0.5° . Techniques need to be developed that prevent scattered light from a bright "point-like" stellar sources from reaching the detector, be it the detector of the BRDF instrument or the science sensor.

(The optical fabrication group highlighted the need for developments in the areas of mid- and high spatial frequency figure measurements; also measurement of subsurface damage.)

Table 35 summarizes the seven technologies for stray light measurement areas.

Table 35. Stray Light Measurement Enabling Technologies Program

TECHNOLOGY	CURRENT TECHNOLOGY	PROGRAM GOALS	NEED DATES	TECH. DEV. TIME FRAME
Stray Light Control	Non-Existent	Onboard Stray Light Control System	'95	Support RADC Research
BRDF	Limited	$\lambda < 0.4 \text{ m}$ $2 < \lambda < 6 \text{ mm}$ $\lambda > 20 \text{ mm}$	ASAP	'93 - '97
Stray Light Testing	Limited, IRAS	System Level Test	'95	'93 - '97
Signatures	Lacking Hardware	Hardware for Polarization Signature Measurements of Scatter/Muller	'95	'93 - '94
Sources and Detectors	VIS and Near IR	More Powerful UV and Far IR Lasers and Detectors to Make BRDF and System Measurements	95	'95 - '99
Scatter Measurements	Visible and Some IR Bands	UV and Far IR Capabilities Very Near Angle Scatter Measurement Capability of $< 0.5^\circ$	ASAP	'94 - '95
Calibration	Limited	Lambertian Reference Materials : UV, IR, Far IR	'95	'93 - '95

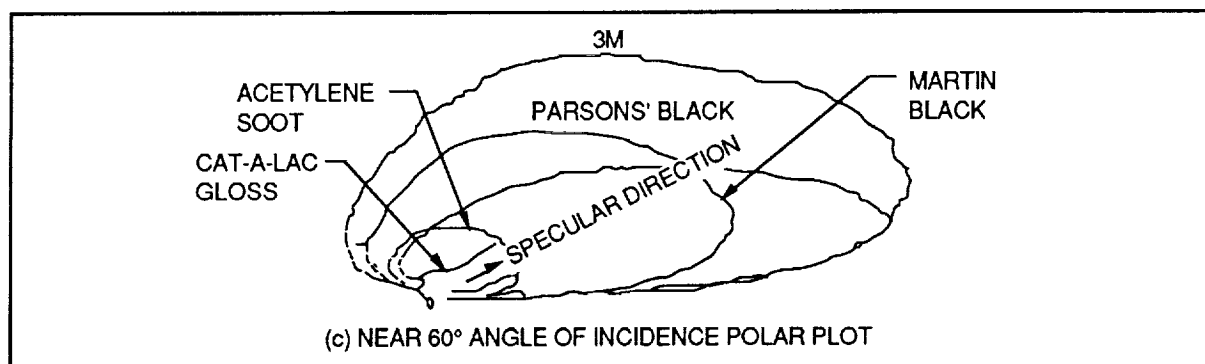
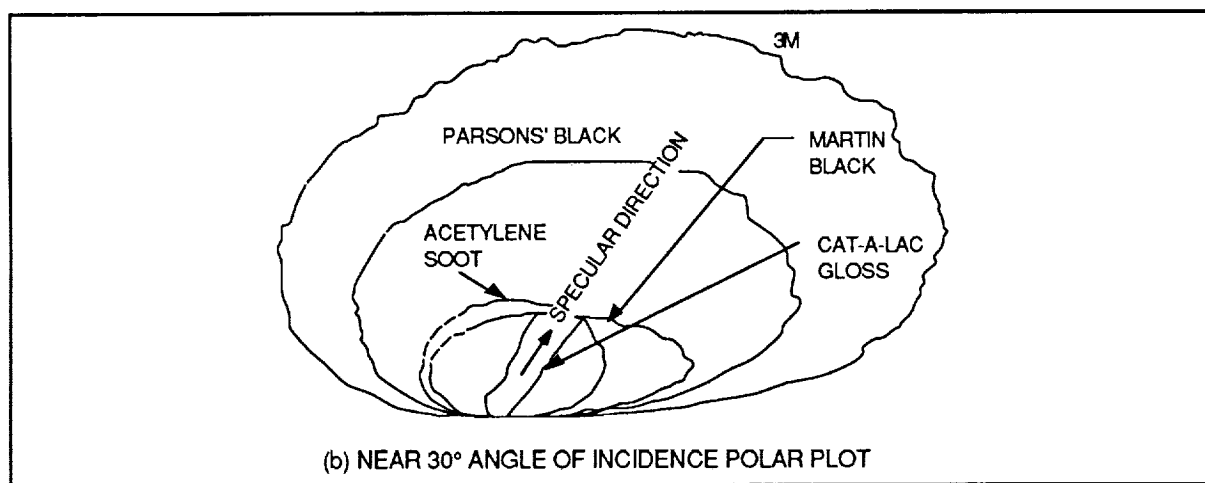
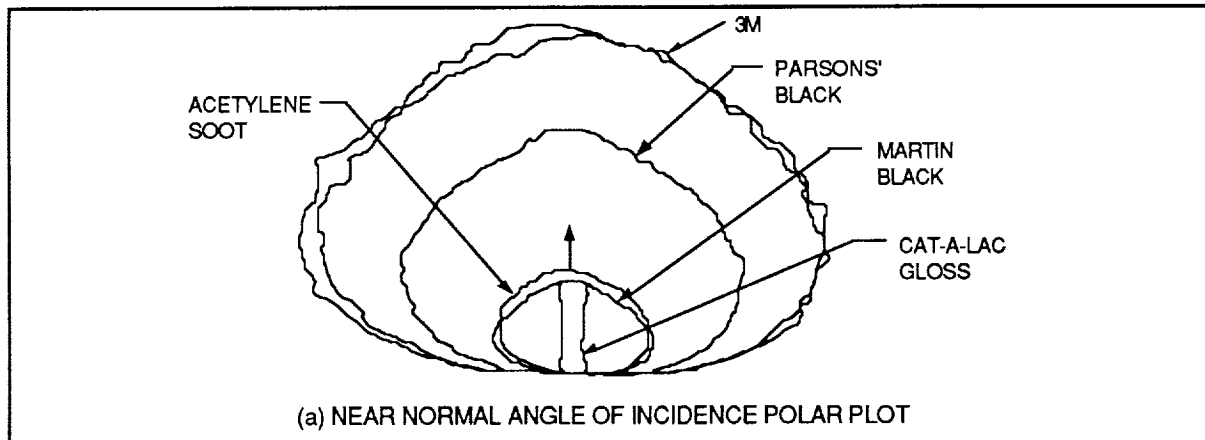


Figure 39. Angle of Incidence Dependence for Black Absorbers.
(Robert Breault, Suppression of Scattered Light, Ph.D. Dissertation, University of Arizona, 1979.)

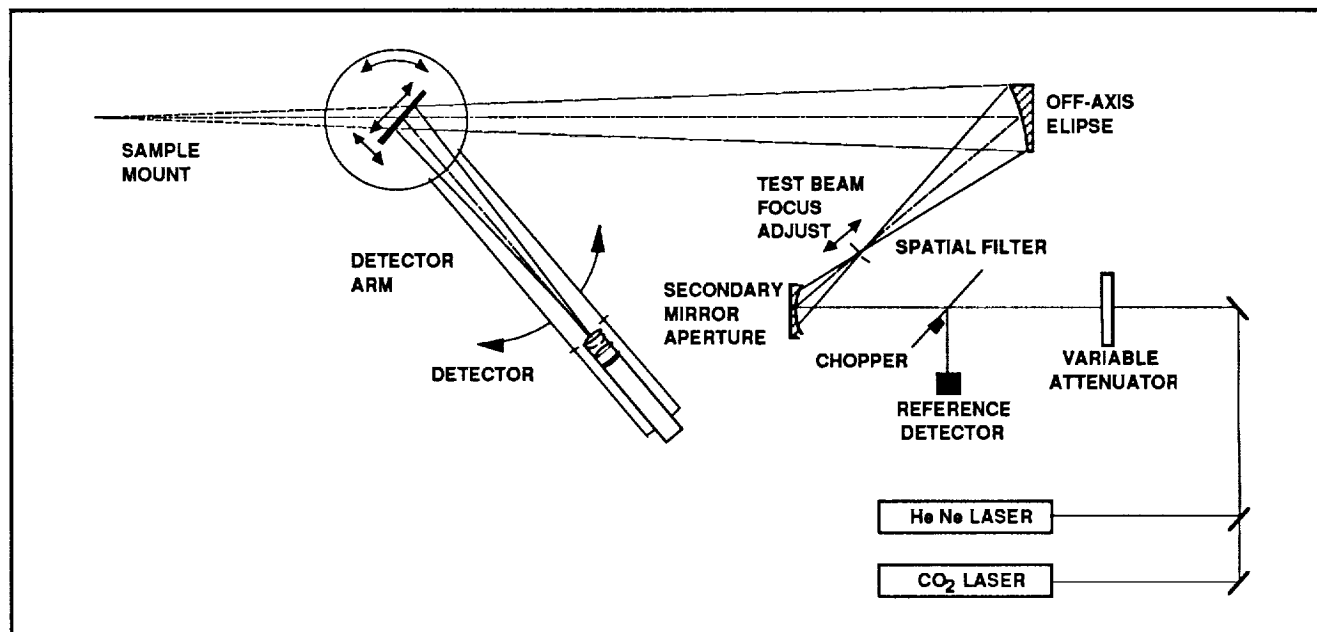


Figure 40. Scatterometer Schematic Diagram. (Courtesy of Breault Research Organization, Inc.)

REFERENCES

1. J. R. P. Angel and P. L. Wizinowich, "A Method for Phase Shifting Interferometry in the Presence of Vibration," *ESO Proc.* 30, 561-567, 1988.
2. M. Kuchel, "Recent Advances In Industrial Optical Inspection," *SPIE*, Vol. 1332, *Optical Testing and Metrology III*, July 1990.
3. P. L. Wizinowich, "Phase Shifting Interferometry in the Presence of Vibration: A new Algorithm and System," *Applied Optics*, Vol. 29, No. 22, 1 August 1990.
4. F. Roddier, "Curvature Sensing and Compensation: A New Concept In Adaptive Optics," *Appl. Opt.* 27, 1223, 1988.
5. F. Roddier, C. Roddier, and N. Roddier, "Curvature Sensing: A New Wavefront Sensing Method," *SPIE*, 976, 203, 1988.

